Row and Column Spaces of a Matrix

Let A be an $m \times n$ matrix.

<u>Defn</u>: The <u>row space</u> of A is the vector space spanned by the rows of A. We denote this space by $\text{row}(A)$. The <u>row-rank</u> of A is $\dim(\text{row}(A))$.

<u>Ex:</u> Let $M = \begin{bmatrix} 3 & 2 & 8 & -1 & 0 \\ 1 & 7 & 6 & 1 & 1 \\ 4 & 1 & 7 & 0 & -5 \end{bmatrix} \leftarrow 3 \times 5$ matrix.

$$\text{row}(M) = \text{span}\left\{ \begin{matrix} [3 \; 2 \; 8 \; -1 \; 0], \\ [1 \; 7 \; 6 \; 1 \; 1], \\ [4 \; 1 \; 7 \; 0 \; -5] \end{matrix} \right\} \leq M_{1,5}(\mathbb{R}).$$

What is row-rank of M? <u>Want</u>: basis!

$$\begin{bmatrix} 3 & 2 & 8 & -1 & 0 \\ 1 & 7 & 6 & 1 & 1 \\ 4 & 1 & 7 & 0 & -5 \end{bmatrix} \rightsquigarrow \begin{bmatrix} 1 & 7 & 6 & 1 & 1 \\ 3 & 2 & 8 & -1 & 0 \\ 4 & 1 & 7 & 0 & -5 \end{bmatrix}$$

$$\downarrow$$

$$\begin{array}{r} \ell_1 = \\ \rightsquigarrow \ell_2 = \\ \ell_3 = \end{array} \begin{bmatrix} 1 & 7 & 6 & 1 & 1 \\ 0 & -19 & -10 & -4 & -3 \\ 0 & -27 & -17 & -4 & -9 \end{bmatrix} \leftarrow$$

<u>observe</u>: last 2 rows are lin indep of one another (not scalar multiples...)

Moreover, $\{\ell_1, \ell_2, \ell_3\}$ is lin indep.

So row-rank of M is 3.

Prop: Suppose A is a matrix. The row space of A has basis the nonzero rows of RREF(A). ◩

↳ A is row-equiv to RREF(A), so

$\text{row}(A) = \text{row}(\text{RREF}(A))\ldots$

Point: To compute a basis of row(A), compute RREF(A) and use the nonzero rows :)

Cor: The row-rank of A is the number of leading 1's in RREF(A).

pf: # leading 1's in RREF(A) = # nonzero rows RREF(A)

Defn: The <u>column space</u> of A is the span of the columns of A. We denote this by col(A). The column-rank of A is dim(col(A)).

Ex: Let $M = \begin{bmatrix} 1 & 3 & 5 & 0 & -2 \\ 2 & 1 & 0 & 1 & 0 \\ 0 & -5 & -10 & 1 & 4 \end{bmatrix}$.

To compute the column space:

$$\text{col}(M) = \text{span}\left\{ \begin{bmatrix} 1 \\ 2 \\ 0 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \\ -5 \end{bmatrix}, \begin{bmatrix} 5 \\ 0 \\ -10 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 4 \end{bmatrix} \right\}$$

Use RREF(M)!

$$\begin{bmatrix} 1 & 3 & 5 & 0 & -2 \\ 2 & 1 & 0 & 1 & 0 \\ 0 & -5 & -10 & 1 & 4 \end{bmatrix} \rightsquigarrow \begin{bmatrix} 1 & 3 & 5 & 0 & -2 \\ 0 & -5 & -10 & 1 & 4 \\ 0 & -5 & -10 & 1 & 4 \end{bmatrix} \rightsquigarrow \begin{bmatrix} 1 & 3 & 5 & 0 & -2 \\ 0 & 5 & 10 & -1 & -4 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\rightsquigarrow \begin{bmatrix} 1 & 3 & 5 & 0 & -2 \\ 0 & 1 & 2 & -\frac{1}{5} & -\frac{4}{5} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \rightsquigarrow \begin{bmatrix} 1 & 0 & -1 & 3/5 & -2/5 \\ 0 & 1 & 2 & -\frac{1}{5} & -\frac{4}{5} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

When we choose a subset of the columns of M and ask about lin. ind., we get a 0-row for any 3 ...

Trying these:

3×2 system $\begin{bmatrix} 1 & 3 & 0 \\ 2 & 1 & 0 \\ 0 & -5 & 0 \end{bmatrix} \rightsquigarrow \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

Interpretation: The first 2 vectors $\begin{bmatrix} 1 \\ 2 \\ 0 \end{bmatrix}\begin{bmatrix} 3 \\ 1 \\ -5 \end{bmatrix}$ are L.I.

Hence: $\left\{ \begin{bmatrix} 1 \\ 2 \\ 0 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \\ -5 \end{bmatrix} \right\}$ is a basis of $\mathrm{Col}(A)$

$\therefore$ the column-rank of A is 2.

NB: Row-rank of this A is also 2 ... $\boxed{\checkmark}$

Prop: Let A be an $m \times n$ matrix. The column space of A has basis

$B = \{ V_i : V_i$ is the i^{th} column of A, RREF(A) has a leading 1 in column $i \}$. $\boxed{\checkmark}$

Cor: The column-rank of A is the number of leading 1's in RREF(A). $\boxed{\checkmark}$

Cor: The row-rank of A is the same as the column-rank of A.

pf: We gave them the same description! $\boxed{\checkmark}$

Defn: The rank of A is $\mathrm{rank}(A) = \dim(\mathrm{row}(A)) = \dim(\mathrm{Col}(A))$.

Defⁿ: The **transpose** of matrix A is the matrix A^T obtained by turning the i^{th} column of A into the i^{th} row of A^T. I.e.

for $A = [a_{i,j}]_{i,j=1}^{m,n}$ we have $A^T = [a_{j,i}]_{j,i=1}^{n,m}$.

Ex: $M = \begin{bmatrix} 1 & 0 & 1 & 5 & 5 \\ 0 & 1 & 0 & 1 & 5 \\ 1 & 1 & 0 & 0 & 0 \end{bmatrix}$, $M^T = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \\ 5 & 1 & 0 \\ 5 & 5 & 0 \end{bmatrix}$.

Observation: ① $\text{row}(A) = \text{col}(A^T)$

i.e. $\text{row}(A^T) = \text{col}(A)$.

② $(A^T)^T = A^{TT} = A$.

Cor: For all matrices A, $\text{rank}(A) = \text{rank}(A^T)$.

Pf: $\text{rank}(A) = \dim(\text{col}(A))$

$= \dim(\text{row}(A^T))$

$= \text{rank}(A^T)$. $\blacksquare$

Recall: Given matrix A, there is a corresponding linear transformation $L_A : \mathbb{R}^n \to \mathbb{R}^m$ for A an $m \times n$ matrix. $L_A(\vec{x}) = A\vec{x}$.

Earlier we defined: $\text{col}(A) = \text{span}\{\text{columns of } A\}$

$\overset{*}{=} \text{ran}(L_A)$

Cor: $Col(A) = ran(L_A)$ and so

$rank(A) = dim(col(A)) = dim(ran(L_A))$.

So we can define $rank(L_A) = rank(A)$.

Even better: $rank(L_A) = dm(ran(L_A))$

A : $m \times n$ matrix $= n - nullity(L_A)$.

$= n - dim(null(A))$.

where $null(A) = \{\vec{x} : A\vec{x} = \vec{0}\}$. *

Let A be $m \times n$. $L_A : \mathbb{R}^n \to \mathbb{R}^m$.

A^T is $n \times m$. So $L_{A^T} : \mathbb{R}^m \to \mathbb{R}^n$,

but $rank(L_A) = rank(L_{A^T})$ ...

Prop: If A is an $n \times n$ matrix, the following are equivalent:

1. $rank(A) = n$.
2. $A\vec{x} = 0$ has a unique solution. *
3. A is nonsingular.
4. the rows of A span $M_{1,n}(\mathbb{R})$
5. the rows of A are lin. indep.

A is said to be non-singular.

$rank(A) = n \to dim(null(A)) = n - n = 0$

$rank(A) = n \to dim(row(A)) = n \to$ rows are a basis of $M_{1,n}(\mathbb{R})$.

$M_{1,n}(\mathbb{R})$

rows (A) are lin indep : n rows $\leadsto$ $dim(row(A)) \geq n$.

⑥ the columns of A span $M_{n,1}(\mathbb{R})$.

⑦ the columns of A are lin. indep.

⑧ Every linear system w/ coeff matrix A has a unique solution.

Remark: ⑧ $\Leftrightarrow$ ② because: ⑧ $\to$ ② trivial.

② $\to$ ⑧ follows from ② $\to$ col(A) has full dimension.

$\to$ columns of A are a basis of $\mathbb{R}^n$

$\to$ ⑧ by unique linear combinations

B a basis of V.

$W \leq V$. $B \subseteq W$.

Then
$$\begin{array}{ccccc} \mathrm{span}(B) & \leq & \mathrm{span}(W) & \leq & V \\ \| & & \| & & \\ V & & W & & \end{array}$$

Hence $V \leq W \leq V \Rightarrow V = W$.

$\mathrm{ran}(L) \leq V$ when $L: W \to V$.

$B \subseteq \mathrm{ran}(L) \Rightarrow V = \mathrm{span}(B) \leq \mathrm{ran}(L)$